Fluidized Bed Combustion of Poultry Litter Demonstration Project

Dr. Stephanie Lansing (Associate Professor)

Abhinav Choudhury (PhD Candidate)

Dr. Gary Felton (Associate Professor)

Prepared for
Maryland Department of Agriculture
50 Harry S. Truman Pkwy, Annapolis,
MD 21401

Prepared by
University of Maryland
Department of Environmental
Science and Technology
College Park MD 20740

Executive Summary:
The Maryland Department of Agriculture's Animal Waste Technology Fund (AWTF) provides incentives to demonstrate new technologies for managing animal manure, including technologies that generate energy from animal manure, reduce on-farm waste streams, and repurpose manure by creating marketable fertilizer. Biomass Heating Solutions USA, Inc. (BHSL) received AWTF funding to demonstrate fluidized bed combustion (FBC) of poultry litter in order to demonstrate renewable energy production and effectiveness in creating a fertilizer and soil conditioner using poultry litter as the feedstock.

The University of Maryland provided third party verification of the energy production efficiency, nutrient transformations during FBC utilization and investigated the sustainability of the process through a life cycle assessment (LCA). Data were obtained for six flocks over sixteen months of monitoring and showed that 45.1% of the poultry litter sample was combustible, with an average moisture content of 39.2%, heating value of 2386 cal/g, and carbon to nitrogen ratio of 7.8:1 prior to combustion. The total energy production was 871 MWh, with 859 MWh in the form of heat and 12.5 MWh in the form of electricity, with a process efficiency of 55.3%. The FBC unit had a total run-time of 3,226 hours (30% of total hours) over the six flocks. The system met Maryland air quality requirements for particulate matter (62% of limit) and NO_x emissions (33% of limit). The FBC process was effective in concentrating the phosphorus and minerals in the poultry litter (568 metric tons) into ash products (23.5 metric tons bed ash and 35.8 metric tons fly ash), comprised of 10.5% (as reported by BHSL) of the raw poultry litter weight with 14.3% phosphorus and 16.2% potassium in the ash products.

The FBC system produced 1.53 MWh of energy (thermal + electrical) per ton of poultry litter (wet mass) combusted based on field conditions over the six flocks averaging 0.176 tons/hr feed rate into the FBC system, 30% annual runtime, and 568 tons of poultry litter combusted. This produced energy is equivalent to 942 MWh of thermal-only energy (1.66 MWh per ton of poultry litter combusted) or 141 MWh of electricity-only (0.249 MWh per ton of poultry litter combusted). If the unit had operated at a higher run-time over the six flocks tested (0.246 tons/hr feed rate into the FBC system, 77% yearly runtime with 1,655 tons of poultry litter combusted), the unit would have produced 1.99 MWh of energy (thermal + electrical) production per ton of poultry litter combusted, which is equivalent to 2.61 MWh of thermal-only energy per ton of poultry litter combusted or 0.391 MWh of electricity-only per ton of poultry litter combusted. The poultry litter contained 24.1 kg N, 19.8 kg P (as P_2O_5) and 24 kg K (as K_2O) on a per ton basis. The ash product (0.105 tons of ash per ton of poultry litter, as reported by BHSL) contained an estimated 144 kg of P (as P_2O_5), and 163 kg of K (as K_2O), with negligible concentrations of N on a per ton basis.

For the LCA, there were two scenarios tested: 1) environmental impacts associated with actual FBC conditions, and 2) results based on a higher biomass feed rate (0.246 tons/hr), yearly run-time (6,720 hours), and a net positive electricity output. The FBC system had 32% and 77% lowered impacts on greenhouse gas emissions compared to LPG usage in the first and second scenario, respectively. The second scenario, overall, had 48 – 98% less impacts on the environment compared to the first scenario, indicating the need for a net positive electrical energy output that can be used for FBC operation and other on-farm operations to increase the sustainability of the process.

1. System Description:

A fluidized bed combustion (FBC) system for poultry litter combustion was installed in Rhodesdale, MD by Biomass Heating Solutions Limited (BHSL). The unit was designed to produce 600 kW of heat for two poultry houses and 65 kW of electrical energy. The performance of the system in terms of energy generation, biomass consumption, ash production, time of operation, and litter and ash characteristics were monitored for 16 months (six flocks) by the University of Maryland. The goal of the technology was to produce energy from poultry litter and create an ash byproduct for use as a fertilizer or soil amendment.

Manure from the poultry houses was removed after each poultry flock. The flock dates that were used in the FBC unit are shown below:

- Flock 1: December 17th, 2016 to February 12th, 2017
- Flock 2: March 8th, 2017 to May 4th, 2017
- Flock 3: May 19th, 2017 to July 18th, 2017
- Flock 4: August 1st, 2017 to September 29th, 2017
- Flock 5: October 18th, 2017 to December 18th, 2017
- Flock 6: January 5th, 2018 to March 5th, 2018

The project's Energy Center housed the FBC unit, the generator, an Organic Rankine Cycle (ORC) unit, and fuel handling system. The litter was stored in a storage shed before being fed into the FBC system using a sensor-controlled scraping system connected to a conveyor belt. The combustion system employed a fluidized bed technology where multiple streams of hot air were used to suspend the fuel particles that were combusted within the furnace. The fluidization of the particles caused an increase in surface area due to the constant turbulence and breaking up of larger particles into smaller sizes. This increased surface area lead to improved contact between the particles and oxygen in air. The ash produced from the combustion process was then transferred to sealed bags for subsequent transport off-farm for use as a fertilizer or soil amendment.

The thermal energy generated by the combustion of the poultry litter was used to heat up the poultry houses by replacing liquefied petroleum gas (LPG). It was also expected that the drier heat would help improve bird health (see report by Jon Moyle at UME). The excess heat was used to power the ORC system for electricity production. The FBC system and the energy center did require electricity input from the grid to operate.

2. Project Monitoring:

The BHSL installed monitoring system measured the energy center output, electricity use, and run-time. Additionally, samples for mineral analyses were collected by BHSL and sent to AgroLabs Inc., Delaware for analysis. Emissions testing was conducted by a third-party vendor to determine if the technology meets Maryland air quality standards.

2.1. University of Maryland-Technology Performance:

Dr. Stephanie Lansing and Dr. Gary Felton, and PhD candidate, Abhinav Choudhury, from the University of Maryland, Department of Environmental Science and Technology monitored the function of the technology, including efficiencies, life cycle, and nutrient budget.

The monitoring requirements for the project during operation included:

1. Tracking and compiling data from the energy center output
    a. Electricity and heat meters to calculate energy delivered to houses and estimate the total thermal and electrical energy produced on a per flock basis.
    b. Tracking of the parasitic load to run the Energy center and FBC system, including circulation pumps, energy center, Organic Rankine Cycle electric generator, and compressors.
    c. Hot water flow temperatures to and from the poultry houses on a per flock basis over the entire study period.
    d. Emission testing for sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter by an independent contractor.
2. Poultry litter and ash quantity and quality
    a. Calorific value, moisture, and volatile solids concentration of the litter and ash collected and analyzed on a monthly basis.
    b. Quantity of poultry litter inputs and quantity of litter converted to ash.
    c. Nutrient value and complete nutrient budget of the litter input and the ash output
3. A life cycle assessment (LCA) to understand nutrients, energy, and carbon flows for the actual conditions and more optimal operational/run-time conditions, including tracking:
    a. Changes in greenhouse gas emissions
    b. Eutrophication potential
    c. Effectiveness of the technology in reducing the cradle to grave environmental impacts
    d. Adverse effects to human health and ecosystem biota.
4. Extrapolation of data for future use
    a. Energy production based on a per tonnage of poultry litter processed for thermal and electric output based on actual conditions and more optimal operating conditions.
    b. The quantity and quality of ash produced based on tonnage of litter processed.

3. Detailed Results:

3.1 Energy Production:

The total energy supplied to the two poultry houses for heating the six flocks was 1,504,727 kWh, which included energy from the FBC unit (858,569 kWh) and energy from back up diesel use when the FBC unit was not operational (646,158 kWh) (Table 1). The temperature of the hot water used for radiant heating of the two poultry houses during FBC operation for each flock are shown in Table 2. The thermal energy production from the FBC unit was more continuous during the initial project period (Flocks 1 – 2 from Dec 2016 – May 2017), with the highest runtime (853 hours), biomass use (198 tons), and amount of energy produced (299,584 kWh) during Flock 1 (Figure 1A). The FBC operated for a total of 3,226 hours and combusted 568 tons of poultry litter, with an average feed rate of 0.176 tons/hr. During Flock 4, the FBC had the lowest runtime (211 hours), thermal energy production (58,186 kWh), and biomass use (38.5 tons) due to repairs and maintenance work on the system. The electrical energy production ranged from 0.7 to 4.0% of the total energy produced per flock, with a cumulative electric energy production of 12,527 kWh during the study period, with most of the potential energy from the poultry litter used for heating the houses and not delivered to the ORC (Figure 1B).

The energy efficiency of the FBC system was consistent, with an average of 55.3% of the calorific value of the poultry litter converted into total energy, with an average of 1,534 kWh/ton poultry litter combusted. The parasitic electric load for operating the FBC unit (131,072 kWh) was higher than the electricity generated during the study period, with a net negative electricity output (-112,700 kWh). BHSL had anticipated operating the FBC system for 6,760 hours annually (77% annual runtime), combusted 1,655 tons of poultry litter annually at a 0.246 tons/hr feed rate. If the unit had operated with these expected parameters, the system output energy production efficiency would have increased to 67.4%, with 1,985 kWh/ton poultry litter combusted.

Table 1: Energy production from the fluidized bed combustion (FBC) system over the six flocks tested.

Flock	Operating Time (hours)	FBC Total Thermal Energy (kWh)	FBC Total Electrical Energy (kWh)	Farm Energy (kWh)	Biomass Use (Metric ton)	Biomass to Energy Conversion Efficiency (kWh/ton biomass)	Efficiency (%)
1	853	299,586	2,144	648,219	198	1523	54.9
2	631	156,031	1,400	256,858	103	1525	55.0
3	819	138,836	3,098	128,033	91.8	1546	55.7
4	211	58,186	2,157	61,722	38.5	1568	56.5
5	482	140,821	1,000	340,278	93.2	1523	54.9
6	229	65,110	2,727	69,618	43.1	1575	56.8
Total	3,226	858,569	12,527	1,504,727	568	1534	55.3

Table 2: Average hot water flow temperatures to and from the poultry houses

Flock Number	Temperature Input (°C)	Temperature Return (°C)	Temperature Difference (°C)
1*	71.9	63.2	8.7
2	75.4	66.2	9.2
3	73.8	66.7	7.1
4	74.5	66.4	8.1
5	85.3	69.2	16.1
6**	82.5	72.6	9.9
Average	77.2	67.4	9.9

*Temperature data for Flock 1 is based on available data from Jan 1, 2017, while the flock start date was December 17, 2016.

**Temperature data for Flock 6 is based on 6 days of operation within the 27-day flock time period (Jan 5th – Jan 31st, 2018).

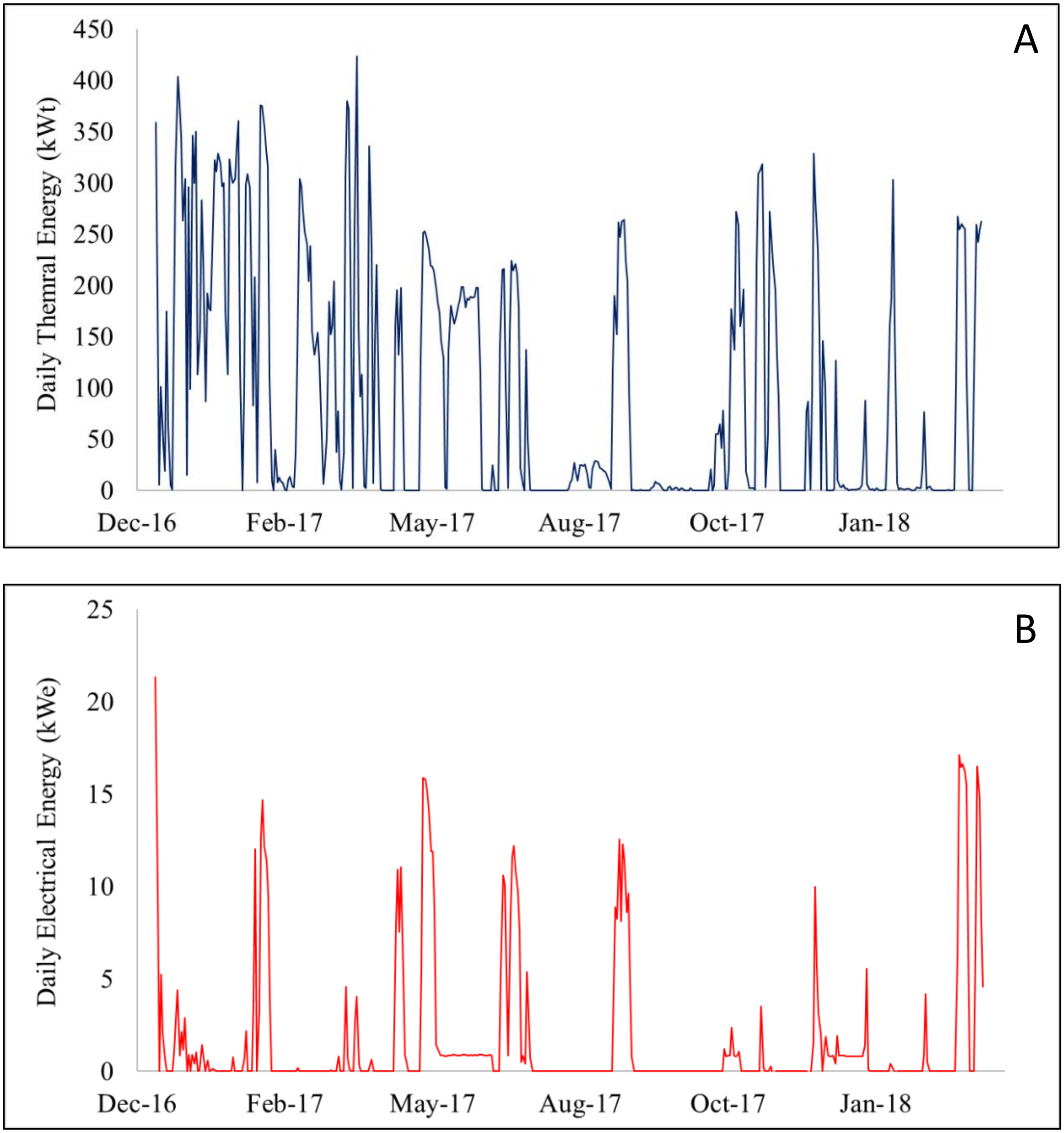

Figure 1. Daily thermal (A) and electrical (B) energy production from the fluidized bed combustion (FBC) unit used to heat two poultry houses and provide electricity over sixteen months (six flocks) of monitoring.

The emission test data for the FBC system is shown in Table 3. All the pollutant concentrations were found to be lower than the air emissions standard for the state of Maryland. Air emissions factor for each pollutant are determined by dividing the rate of pollutant emissions (g/hr) by the heat input (MMBtu/hr) for a biomass combustion system. For heat inputs between 1.5 – 10

MMBtu/hr, particulate matter emissions factor standard is 104.3 g/MMBtu, and NO_x emissions factor standard is 136.1 g/MMBtu. There are no emission factor standards for sulfur dioxide (1.44 g/hr), carbon monoxide (215 g/hr) and volatile organic carbon (1.63 g/hr). The BHSL FBC system had a particulate matter emissions factor of 63.50 g/MMBtu (62% of limit) and a NO_x emissions factor of 45.4 g/MMBtu (33% of limit). MDE limits are detailed in "COMAR 26.11.09.12 (D) – Requirements for Biomass Fuel-Burning Equipment Greater than 1.5 MMBtu/hr and Less Than 10 MMBtu/hr Heat Input Capacity".

Table 3: Emission test results for the FBC system with a heat input of 2.7 MMBtu/hr

Contaminants	**Emissions (g/hr)**	**Emission rate (g/MMBtu)**	**Emission Standard (g/MMBtu)**
Filterable Particulate Matter	6.3 ± 2.6	2.33	N/A
Condensable Particulate Matter	163 ± 7.8	60.5	N/A
Total Particulate Matter	170 ± 5.2	62.8	104
Nitrogen Oxide	120 ± 42	44.4	136
Sulfur Oxide	1.4 ± 0.2	0.54	N/A
Carbon Monoxide	215 ± 69	79.5	N/A
Volatile organic carbon	1.6 ± 0.5	0.60	N/A

3.2 Poultry Litter and Ash Product Characteristics:

The heating value of the poultry litter varied from 2,055 to 2,737 cal/g (average 2386 cal/g), while the volatile solids (VS) content varied from 40.1% to 56.7% (average 45.1%). The dry matter content of the poultry litter averaged 60.8%. The two parameters followed a similar trend, with higher VS fractions leading to higher heating values (Figure 2).

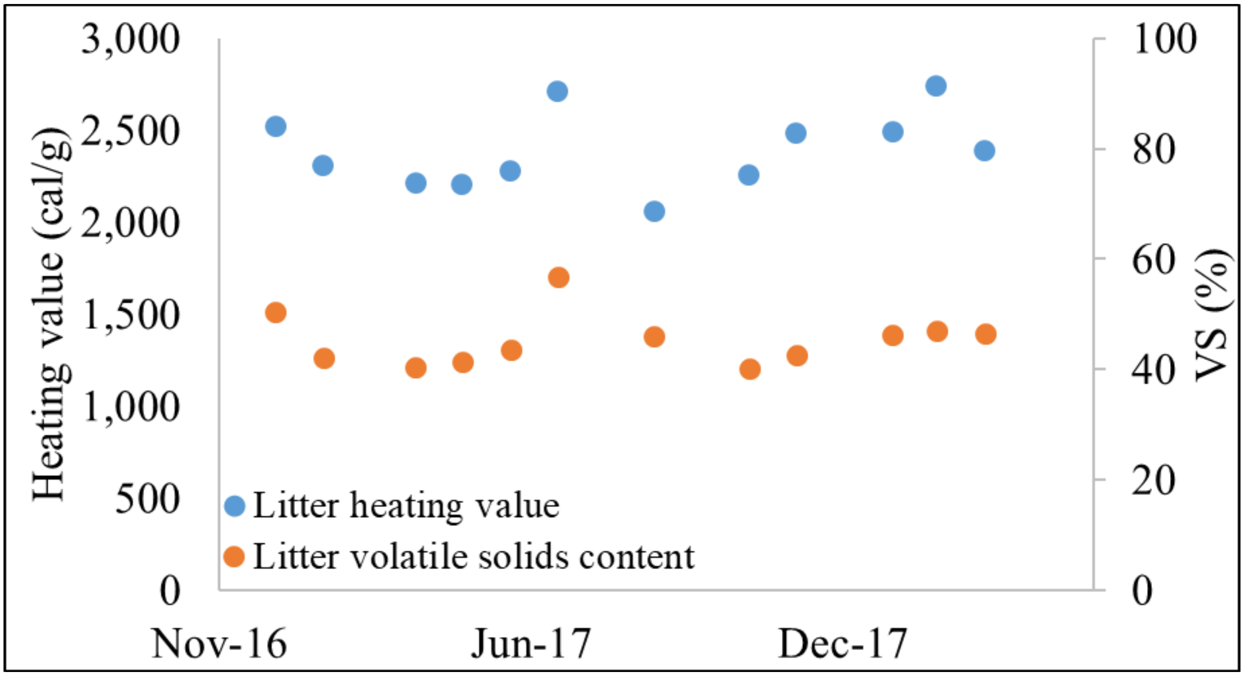

Figure 2. Heating value and volatile solids (VS) variation over 16 months of sampling.

The mineral composition of the poultry litter, bed ash, and fly ash are shown in Table 4. The results show that the combustion process concentrated the non-volatile minerals in the ash product, with the fly ash having a higher concentration of the minerals than the bed ash.

Table 4: Mineral composition of the poultry litter, bed ash, and fly ash

Elements	Poultry Litter	Bed Ash	Fly Ash
Sulfur (%)	0.71 ± 0.0	3.4 ± 0.3	4.4 ± 0.3
Sodium (%)	0.63 ± 0.0	3.0 ± 0.3	4.6 ± 0.3
Calcium (%)	1.74 ± 0.2	9.1 ± 1.0	9.3 ± 0.8
Magnesium (%)	0.49 ± 0.1	2.3 ± 0.3	2.7 ± 0.2
Zinc (ppm)	469 ± 22	2274 ± 288	2565 ± 168
Iron (ppm)	548 ± 92	3506 ± 186	4515 ± 174
Manganese (ppm)	355 ± 21	1840 ± 232	2256 ± 146
Copper (ppm)	254 ± 13	938 ± 87	1767 ± 147
Aluminum (ppm)	206 ± 23	2131 ± 153	2810 ± 116

The amount of poultry litter processed, and ash produced (bed ash and fly ash), with the average nutrient concentrations from the six flocks are shown in Table 5. The FBC system combusted 568 tons of poultry litter and converted it to 59.3 tons of ash, which is 10.5% of the original mass of poultry litter. Plant macronutrients with a fertilizer value, namely, potassium (K) and phosphorus

(P) in the poultry litter were also concentrated in the ash product. The bed ash and fly ash had an average P content of 13.4% and 15.0%, respectively, and an average K content of 11.4% and 19.4%, respectively. Most of the P (63%) and K (72%) were concentrated in the fly ash fraction. The ash contained negligible concentrations of carbon (C) and nitrogen (N), as the combustion process resulted in complete conversion of C and N into its gaseous forms. On a per ton basis, the wet poultry litter contained 24.1 kg of N, 19.8 kg of P and 24 kg of K. The bed ash and fly ash formed 39.6% (23.5 tons) and 60.4% (35.8 tons) respectively, of the total ash produced. The bed ash contained 134 kg of P (as P_2O_5) and 114 kg of K (as K_2O) on a per ton basis, while the fly ash contained 150 kg of P (as P_2O_5) and 194 kg of K (as K_2O) on a per ton basis. The mixed ash product (bed ash + fly ash) contained an estimated 144 kg of P (as P_2O_5), and 163 kg of K (as K_2O), with negligible concentrations of N on a per ton basis.

Table 5: Overall nutrient load reductions for all flocks and their respective fractions in the bed ash, fly ash, and total ash product.

Poultry Litter (568 metric tons combusted)		
Nutrient	**Concentration (%)**	**Mass of nutrient (kg/ton poultry litter)**
Nitrogen (% N)	2.41	24.1
Phosphorus (% P_2O_5)	1.98	19.8
Potassium (% K_2O)	2.40	24.0
Bed Ash (23.5 metric tons generated)		
Nutrient	**Concentration (%)**	**Mass of nutrient (kg/ton bed ash)**
Nitrogen (% N)	0	0.0
Phosphorus (% P_2O_5)	13.4	134
Potassium (% K_2O)	11.4	114
Fly Ash (35.8 metric tons generated)		
Nutrient	**Concentration (%)**	**Mass of nutrient (kg/ton fly ash)**
Nitrogen (% N)	0.2	2
Nitrogen (% N)	15	150
Phosphorus (% P_2O_5)	19.4	194
Total Ash (59.3 metric tons generated)		
Nutrient	**Concentration (%)**	**Mass of nutrient (kg/ton ash)**
Nitrogen (% N)	0.1	1
Phosphorus (% P_2O_5)	14.4	144
Potassium (% K_2O)	16.3	163

It should be noted that the total ash mass in Table 5 was as reported by BHSL . UMD could not verify the data. Using BHSL reported data did not result in complete mass conservation of P and K in the ash (24% loss in P and 29% loss in K). The reported mass loss using BHSL data was 89.5% (59.3 tons of ash). However, a 100% mass conservation of P and K would have resulted in an average total ash production of 80 tons of ash (86% mass loss or 141 kg/ton of poultry litter) with the same concentration of P and K (14.4% P and 16.3% K in the mixed ash product).

3.3 Life Cycle Assessment Results:

Life cycle assessment (LCA) quantifies the inputs and outputs of a system, product, service or a process, and evaluates the environmental impacts associated with the system. LCA is most commonly used in comparing the environmental impact of a product or service with a comparable alternative in order to determine which product has a lower environmental impact. LCA can also be used to estimate the environmental impact of a product at each stage of its life (cradle to grave) in order to possibly minimize the environmental impacts of the stages that have the highest negative impacts. The LCA in this analysis was used to evaluate and track the effectiveness of the FBC technology in reducing the cradle to grave environmental impacts when compared to the use of liquid program gas (LPG) for heating the poultry houses.

This life cycle assessment study followed the ISO 14040 and 14044 standards. The lifecycle assessment of the nutrients, energy, and carbon flows were performed using SimaPro software (Version 9.0) developed by PreConsultants. The environmental impacts were estimated using the ReCiPe 1.10/World (May 2014) midpoint (H) impact assessment method. The following 18 impact categories included in this method were estimated: climate change potential (CCP), ozone depletion potential (ODP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), human toxicity potential (HTP), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity potential (TEP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), ionizing radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO) ,natural land occupation (NLO), metal depletion (MD), fossil depletion (FD), and water depletion (WD).

The impacts of manure production were not included in the study, as poultry is bred for meat and eggs, and not for the manure. As such, the impacts associated with poultry production would be the same for all the studied scenarios. Two main scenarios were considered for the impact assessment:

1. Baseline scenario: impacts from the actual operating conditions and outputs of the FBC unit monitored over the study period was used.
2. Optimal scenario: assuming the FBC system had a higher run-time (47% increase) and produced energy more efficiently (15% increase).

The functional unit for the impact assessment was defined as the 'generation of 1 MJ of energy'. The functional unit allows for comparison between the environmental impacts associated with different products. The input and output flows of the system were normalized based on the total amount of energy produced from poultry litter combustion after sixteen months of monitoring. The calculations allowed for the inputs, outputs and environmental impacts to be presented on a per MJ of generated energy basis, i.e. the functional unit. During this time, the FBC system operated for 3,226 hours and processed 568 metric tons of poultry litter.

The life cycle assessment of the FBC system showed that CCP of poultry litter combustion was 32% less than the CCP associated with liquid propane gas (LPG) production and use (Figure 3). The total CCP impact of combusting poultry manure was a combination of direct emissions of greenhouse gases (GHGs) and upstream emissions originating from the construction and assembly of the plant, emissions associated with storage of poultry litter, start-up diesel use, and electricity required for daily operation of the FBC system. It was expected that the FBC system would produce excess electricity, especially during the summer when heating requirements are lower. However, due to the system not operating at a high capacity/runtime throughout most of the study period, the electricity produced was not sufficient to offset the parasitic load required for daily operation of the system. As a result, the FBC system consumed electricity from the grid and it resulted in negative impacts on CCP. The FBC process was also not effective at lowering freshwater and marine eutrophication potential compared to LPG use for space heating.

In the more optimal operating condition scenario, the combustion process had 66% less impact on CCP than the baseline scenario due to an increased biomass feed rate, yearly run-time (6,720 hours), and energy output/biomass feed ratio (Figure 4). In the base scenario (30% runtime), the hourly feed rate was 0.176 tons/hr, while in the more optimal scenario, it was calculated to be 0.246 tons/hr (detailed in Section 3.1). The net positive renewable electricity led to avoided impacts on CCP (77% lower than LPG use) from the production of electricity from fossil fuel sources. The reduction in freshwater eutrophication was 75.7% less than LPG use. In addition, the reduction in all other environmental impacts due to the improved efficiencies in the more optimal scenario ranged from 48 – 98% when compared to the actual conditions in the baseline scenario.

Combustion of poultry litter was only effective at reducing impacts on terrestrial ecotoxicity (by 35.4%) compared to LPG use. Impacts on human toxicity, freshwater, and marine ecotoxicity were all higher than impacts associated with LPG use for space heating. The avoided use of LPG was only able to offset the environmental impacts associated with six out of the eighteen impact categories in the baseline case (Figure 3). However, a more optimal performance would have led to net environmental gains in fourteen impact categories, including, freshwater and marine ecotoxicity, indicating the necessity for improved efficiencies for heat and electricity production when operating the FBC unit (Figure 4).

Overall, the results showed that poultry litter combustion for energy generation can be a sustainable alternative disposal technology, especially in places where land application is restricted, such as areas with high concentration of poultry farms, like the Chesapeake Bay region. The life cycle assessment of the FBC system showed that it is possible to obtain net environmental gains from poultry litter combustion for heating poultry houses and renewable electricity production. Due to the complications associated with the operation of the FBC system, it was not able to function optimally (lower than expected biomass feed rate, operating hours, and energy output/biomass feed ratio) and resulted in a net negative electricity output. A positive electricity output would have led to a more sustainable alternative disposal technology for poultry litter.

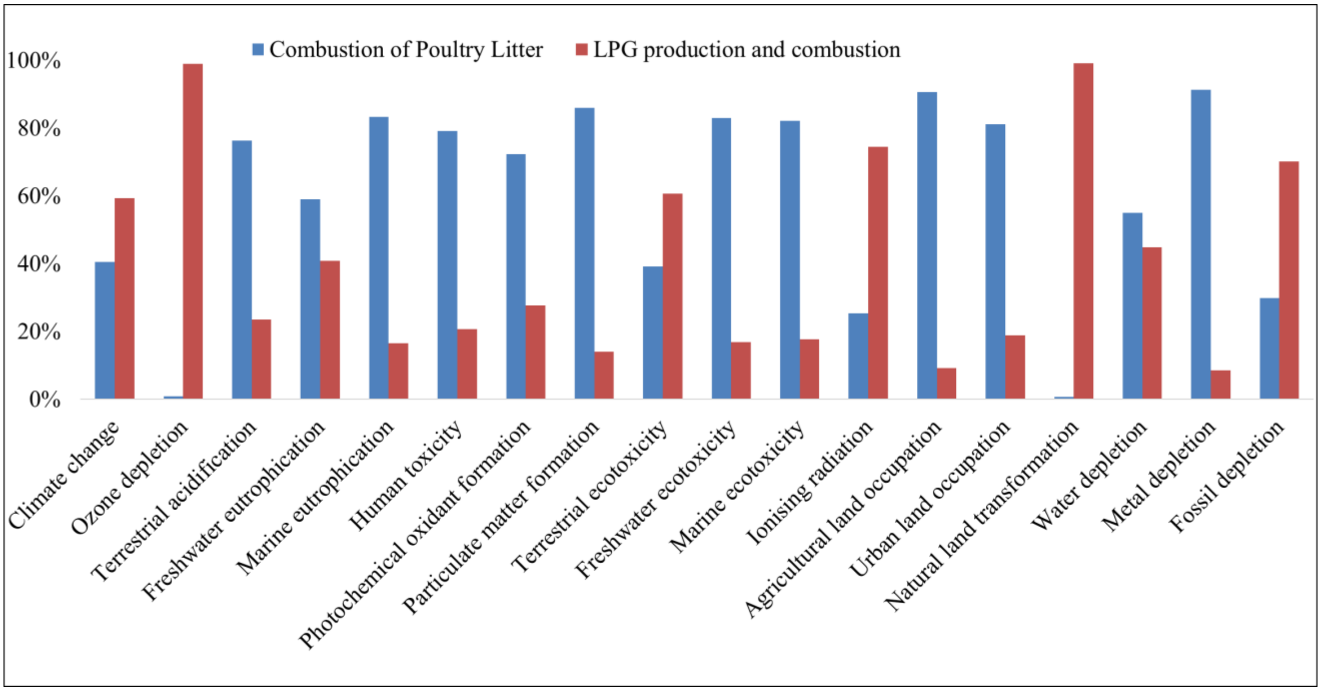

Figure 3. Environmental impacts of poultry litter combustion in the baseline scenario compared to LPG production and combustion.

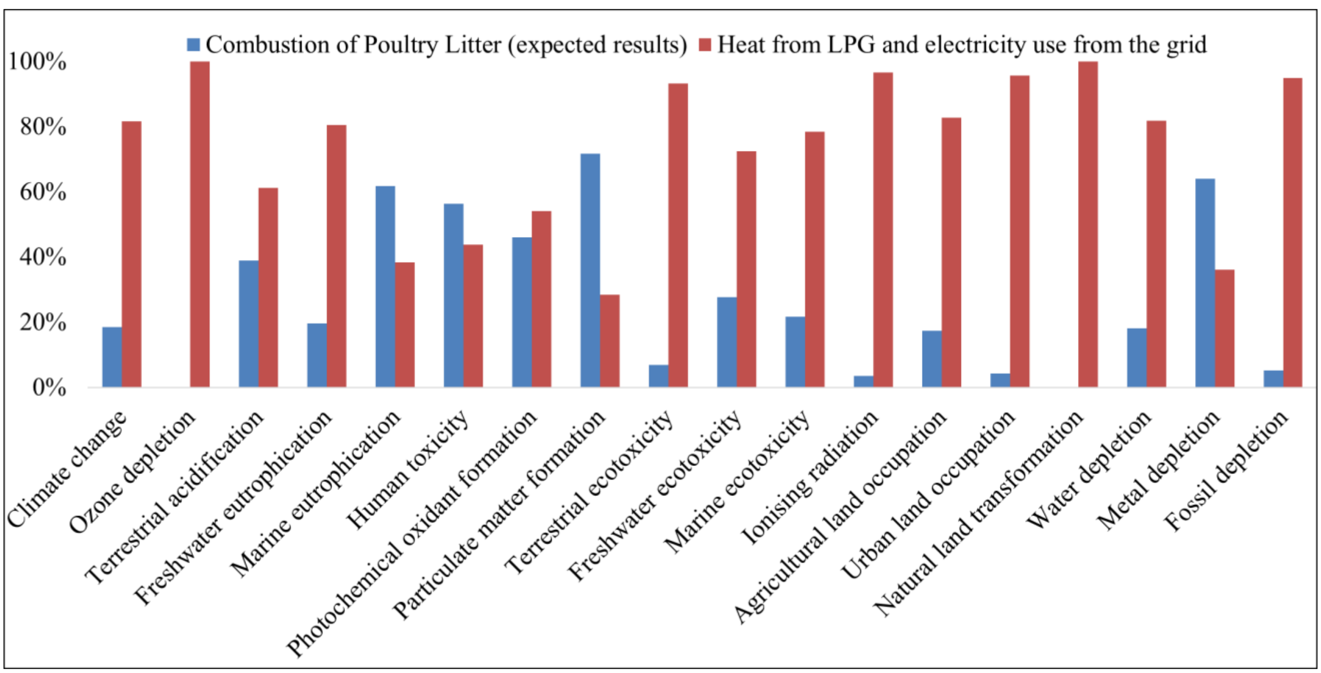

Figure 4 Environmental impacts of poultry litter combustion with renewable energy production in the more optimal scenario compared to LPG production and combustion and replacement of electricity production in Maryland.

3.4 Information for Farmers/Extrapolation of Results:

The amount of poultry litter combusted, and the total energy produced during each flock varied due to the operational challenges faced by BHSL. However, the energy production (thermal and electrical) per ton of poultry litter processed was consistent throughout the study period. The results of the study showed that the FBC system produced an average **1,534 kWh of total energy per ton of poultry litter (wet mass)** based on the actual conditions over the six flocks averaging 0.176 tons/hr feed rate into the FBC system, with a 30% annual runtime and 568 tons of poultry litter combusted. This produced energy is equivalent to 942,000 kWh of thermal-only energy (1,660 kWh per ton of poultry litter combusted) or 141,000 kWh of electricity-only (249 kWh per ton of poultry litter combusted).

If the unit had operated at a higher run-time over the six flocks tested (0.246 tons/hr feed rate into the FBC system, 77% yearly runtime with 1,655 tons of poultry litter combusted), the unit would have produced 1,985 kWh of energy (thermal + electrical) production per ton of poultry litter combusted, which is equivalent to 2,610 kWh of thermal-only energy per ton of poultry litter combusted or 391 kWh of electricity-only per ton of poultry litter combusted

An estimated 104.5 kg of ash per ton of wet poultry litter was produced from the combustion process, a mass reduction of 89.5% from the original wet poultry litter (as reported by BHSL). However, the BHSL reported data showed a 24% and 29% mass loss of P and K, respectively. Assuming a 100% mass conservation of P and K, a mass reduction of 86% would have been expected with a total ash production of 144.1 kg of ash per ton of wet poultry litter. The wet poultry litter contained 24.1 kg of N, 19.8 kg of P (as P_2O_5), and 24 kg of K (as K_2O) on a per ton basis. The ash product contained an estimated 144 kg of P (as P_2O_5), and 163 kg of K (as K_2O), with negligible concentrations of N, on a per ton basis.

The life cycle assessment of the FBC system showed that it can lead to **32% lowered impacts on greenhouse gas emissions compared to LPG usage**. However, the process was not effective at lowering freshwater and marine eutrophication potential. Assuming the system operated as expected without the challenges faced by the operators, **the reduction in greenhouse gas emissions and freshwater eutrophication would have been 77.4% and 75.7%**, respectively, compared to LPG use for poultry house heating. It should be noted that the LCA study did not include the impacts of land application of poultry litter and the ash product due to the large variation in emissions caused by factors such as manure characteristics, application management, soil conditions, and environmental factors.

4. Project Implementation

The Murphy family own and operate a total of 16 poultry houses. The farm site where BHSL system was implemented, Double Trouble, consists for 4 poultry houses growing on average a total of five flocks each year. The Murphy's sell most of the poultry litter they produce, and it is transported off farm. A few factors impacted the implementation of the project and may have influenced the outcomes. They include:

4.1 Project Engineering and Design

- The change of the project location resulted in a change of the utility company and unplanned cost for a three-phase power system. By changing to Choptank electric, the cost to hook up to three-phase became enormously high, because there was no nearby three phase service. In an effort to reduce costs, the FBC system was re-designed to utilize single phase power and, where needed, convert to three-phase power Changes to the design or the equipment may have contributed to issues with system operation and its capacity for generating energy.

- The FBC systems successfully operated in the United Kingdom were fabricated in Ireland. The equipment for the system installed in Maryland was fabricated in South Korea in an effort to reduce the price point of the system. Although after completion it was shipped to Ireland for testing and then repackaged and shipped to the Double Trouble farm. There may have been changes to the materials used or quality controls in place that impacted the operation and maintenance costs of the system and contributed to lengthy down times.
- Poultry litter originating from Maryland was processed by one of the FBC systems operating in UK, and no needed system modification were expected. Once the system started operation in the US, it was determined that the feedstock contained rocks and other foreign material, causing severe damage to the unit. As a result, a screening device was added to the system to prevent rocks from entering the FBC and a large magnet was installed to remove foreign metal matter from the poultry litter to prevent damage to the machinery.

4.2 Project Maintenance

- There were issues obtaining parts when system breakdowns occurred. The initial system and subsequently a majority of the parts required for its maintenance and repair were purchased from manufacturers outside the U.S. and took three to twelve weeks to secure and install.
- The mixed source of parts resulted in mismatches. Mixing hose and piping with metric and English units resulted in leaks. Having electronics that worked on 50 hz and 60 hz resulted in incorrect data.
- The out of country sourcing of parts stymied the involvement of U.S. subcontractors to assist with onsite trouble shooting and repairs.

4.3 Project Management

- BHSL personnel responsible for system design, procuring equipment, overseeing implementation, managing its operation, and supporting IT changed throughout the project period. There was a lack of consistency among individuals when making decisions or trying to resolve problems.

5. Lessons Learned

- Frequent communication and specific, written expectations of each party throughout the project is integral to a successful project. There needs to be a consistent point-person throughout both the implementation and monitoring periods to communicate with the farmer, MDA and monitoring representatives on project changes, concerns, and expectations, including responsibilities for land, equipment, and operation after the required monitoring period is finished.
- The quality and characteristics of the feedstock need to be carefully tested before system

design and installation. Poultry litter contaminated with foreign objects damaged to the FBC unit and resulted in downtime for repairs.

- The US feedstock quality had a lower calorific value and higher moisture content compared to the earlier BHSL installations. The FBC can combust fuels with heating values (LHV) under ideal conditions of 8 MJ/kg, with a tolerable range of 7.5 MJ/kg plus (LHV), and an ideal moisture content of 40%, with a tolerable range of 35 to 45%. The poultry litter feedstock from Murphy's farms had an LHV varying from 6.88 to 9.07 MJ/kg and moisture content ranging from 31.3% to 46.5%.
- The equipment quality may have been adversely impacted by changing its fabrication from Ireland to South Korea.

6. Conclusions

The results showed that poultry litter combustion is a waste-to-energy process is possible in the US, with thermal and electric energy production. The life cycle assessment of the FBC system showed that it is possible to obtain net environmental gains from poultry litter combustion for heating poultry houses and renewable electricity production especially in the climate change potential category. The FBC system was not able to function optimally (lower than expected biomass feed rate, operating hours, and energy output/biomass feed ratio), resulting in a lower than expected total energy output and an overall net negative electricity output. Differences in poultry litter characteristics between the US and British sources included a lower calorific value in the US feedstock, varying moisture content, and the increased presence of foreign matter that interfered with the combustion process.

Based on the results of the monitoring study, an hourly input rate of 0.176 tons/hr (30% runtime) of poultry litter resulted in a thermal energy production rate of 266 kWh and electricity production rate of 3.88 kWh. However, higher operational runtimes (0.246 tons/hr, 77% runtime with a yearly total of 6,720 hours) would have led to an estimated thermal energy production rate of 462 kWh and an electricity production rate of 26.9 kWh. The poultry litter contained an average 24.1 kg of N, 19.8 kg of P (as P_2O_5), and 24 kg of K (as K_2O) and produced 104.5 kg of total ash product on a per ton basis. The ash contained an estimated 144 kg of P (as P_2O_5), and 163 kg of K (as K_2O), with negligible concentrations of N, on a per ton basis.